

# Planetary Data System Requirements

## Multi-Mission Radio Science Requirements for the 1978 to 1988 Era

Edited by  
H. T. Howard

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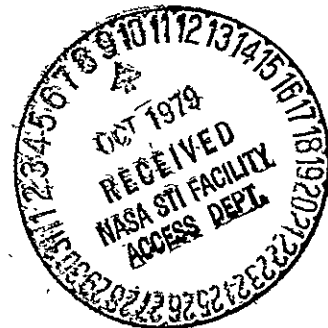
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National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California



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## ABSTRACT

The functional and performance requirements for support of multi-mission radio science are established. The classes of radio science investigation are described and the needed data is discussed. This document is for a sliding ten year period and will be iterated as the mission set evolves.

## ACKNOWLEDGEMENT

This document was prepared by the Multi-Mission Radio Science Coordinating Team of the Jet Propulsion Laboratory End to End Information System and was edited by H.T. Howard.

## CONTRIBUTORS

The Multi-Mission Radio Science team was chartered under the Jet Propulsion Laboratory End to End Information System to establish functional and performance requirements which support radio science and celestial mechanics investigations.

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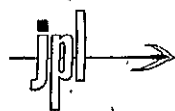
## I. INTRODUCTION

- A. The purpose of this document is to establish functional and performance requirements which will support multi-mission radio science and celestial mechanics investigations. This will be done by developing the scientific rationale for the various types of investigations and extracting the system requirements in engineering terms. An additional purpose is to provide the mechanism for continuing two-way communication between the scientific and engineering communities so that the best advantage can be taken of future developments in both areas.
- B. The goal is to plan for a sliding ten year period beginning with the present systems and current mission set, and to iterate this plan as the system evolves and new missions are studied and proposed. The planning will encompass the End-to-End Information System from the spacecraft, through the Deep Space Network and the data systems, to deliverable data products. The definitions below are included to put a boundary around the territory to be discussed in this document:
- C. Radio Science and Celestial Mechanics are those investigations which use radiometric data obtained from ground-to-spacecraft and spacecraft-to-ground radio links to study the fundamental laws of gravitation, the interplanetary medium, the sun and its corona, and the characteristics and environments of the planets, their various satellites, and other bodies including comets and asteroids.
- D. The End-to-End Information System includes all elements which can affect the quality of radiometric data. The end-to-end system thus begins at the Deep Space Station (DSS) goes roundtrip through the

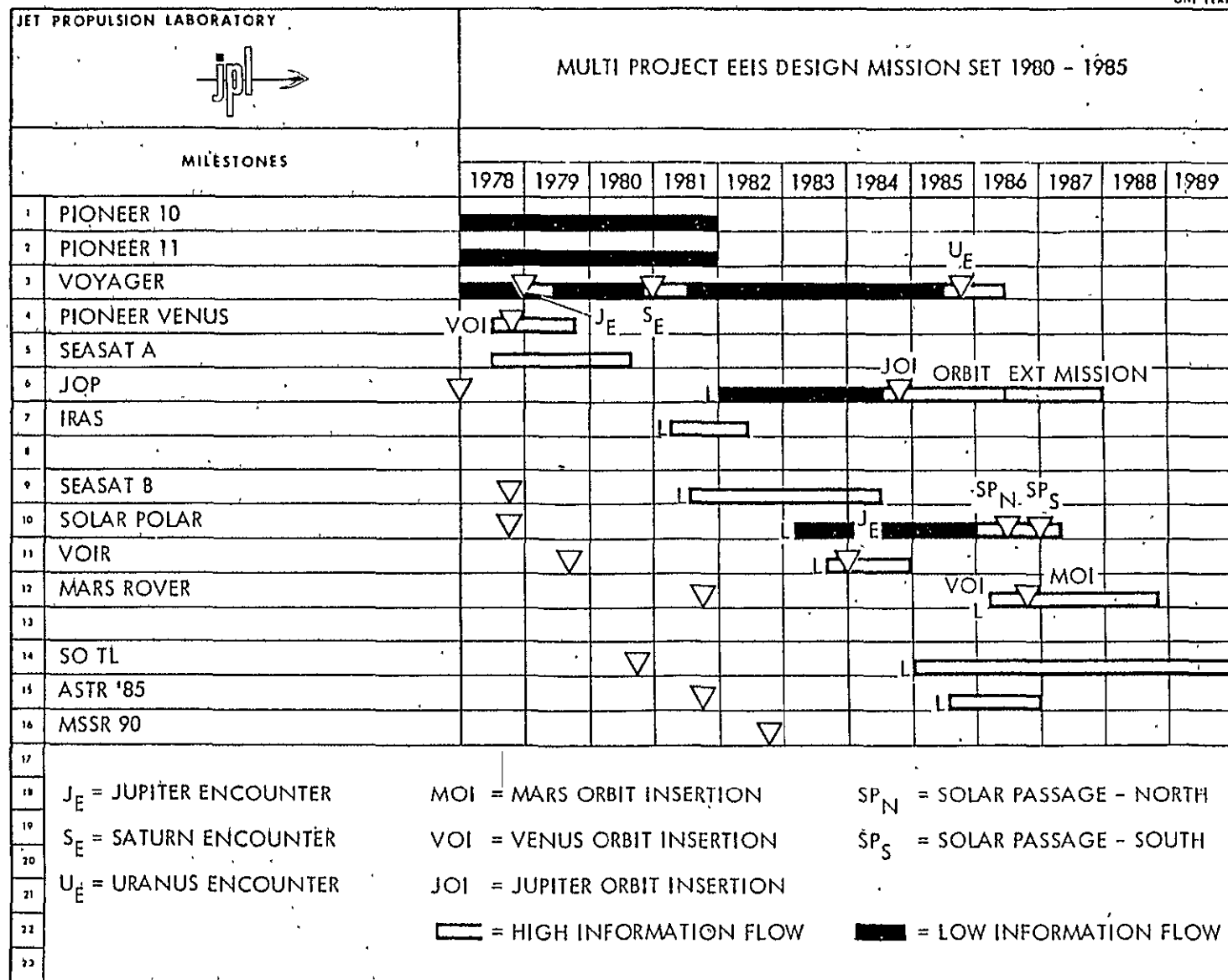


spacecraft radio, the DSS receiving system, the Ground Communication Facility, the Mission Control and Computing Center (MCCC), the Navigation computing facility, and ends with tapes in the hands of an investigator. The concern of this document therefore includes spacecraft and ground system technical performance and engineering support as well as data handling and processing.

The Multi-Project EEIS mission set shown in Figure I-1 has been used to provide a set of initial conditions for the following sections. As new missions are approved and as results come in from present ones, this document will be revised.



ONE YEAR



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Fig. I-1. Multi Project EEIS Design Mission Set 1980-1985

## II. SCIENCE RATIONALE:

### DATA TYPES AND THEIR SCIENTIFIC USES

Virtually all of the characteristics of the electromagnetic signals radiated to and from the earth stations and the spacecraft can be and have been used as tools for scientific investigation. To be useful scientifically the radiated and transponded characteristics of these signals must be controlled and measured with a precision that is order(s) of magnitude better than the size of the effects to be observed. The basic observables are as follows:

1. Frequency/Phase
2. Amplitude
3. Polarization
4. Angle of Arrival
5. Time of arrival/Range

Frequency, amplitude, polarization and time of transmission can be precisely controlled and all of them can accurately measured upon return to earth. They are affected in different ways by the motion of the earth, the spacecraft and the various regions through which the signal propagates and thus can be used to separate, for example, plasma events from gravity field perturbations.

The time history of each parameter is of prime interest; it should also be noted that the ability to separate effects and to do it precisely depends upon performing all of the measurements simultaneously, often at more than one frequency. Missions in the near future will be conducted

using S (2.1 to 2.3 GHz) and X (8.0 to 8.5 GHz) bands, while K<sub>a</sub> (~13 GHz) band is emerging in long term DSN planning, and L (~1 GHz) band beacons have been requested by several investigators.

In the following section each of the currently known investigation areas is presented individually with a discussion of the data types and accuracies necessary to perform meaningful experiments. There is some overlap in the discussions because the propagation medium effects can be similar to, and sometimes larger than, those of the planets' gravity fields and environment. In other words, one investigator's noise is another's data although it is possible in many cases to separate the two.

Once the sizes of individual effects are known and their interactions understood, it will be possible to develop detailed functional and performance requirements for the system. These will be the subject of Section III.

11. A. PLANETARY GRAVITY FIELDS AND COMPOSITION,  
ATMOSPHERES, IONOSPHERES, MAGNETIC FIELDS, SURFACES, AND RINGS

CELESTIAL MECHANICS

Radio tracking observations of changes in the velocity vectors of spacecraft, as they fly near the planets and their satellites, are used to define the gravitational fields. For each of the primary targets (e.g., planet or satellite), the total mass and several higher mass moments can be determined from a flyby trajectory. Orbiters of the planets and satellites can be used also to obtain more detailed information on the gravitational fields.

The scientific rationale for obtaining gravitational data differs, depending on whether the concern is with the terrestrial or the giant planets, and, more fundamentally, whether the information will be used for planetary studies or for a study of the nature of gravitation itself. For purposes of experimental gravitation, the values of planetary mass are needed in order to use planetary motions to test theories of gravitation at the post-Newtonian limit of  $10^{-8}$  or less. Once the masses are determined accurately by spacecraft flybys, these masses can be treated as known parameters in least squares fits to the planetary radiometric and astrometric data. This procedure can lead to a superior test of gravitational theory than would be the case if the masses had to be treated as unknowns.

For purposes of planetology, the justification for gravitational data differs for the terrestrial and giant planets. The latter are probably very near to hydrostatic equilibrium on a global scale, and hence it is possible to study the interior structure of the planet by

making measurements on its external gravitational field. The terrestrial planets, on the other hand, are not in hydrostatic equilibrium, and studies of their interiors involve an analysis of the gravitational data in conjunction with planetary topographic information (Sjogren et al., 1976).

The primary question for the terrestrial planets concerns the degree of isostatic compensation of the surface topography, while the primary question for the giant planets concerns the absolute magnitudes of the even zonal gravitational harmonics and how they are related to the distribution of mass in the interior.

### Terrestrial Planets

The acquisition of both gravitational and topographic data is essential to a study of the terrestrial planets. Earth-based photography, star occultations, and Earth-based radar provide good data over limited areas for lunar and planetary topography. Polar orbiting spacecraft can provide more detailed topographic maps and also more complete coverage. In the future, laser and radar altimeters will be extensively used to obtain even better topographic data.

The removal of topographic effects (Bouguer correction) from the primary gravity to a scale consistent with the overall analysis leaves the anomalous gravity due to internal density variations only, the Bouguer gravity. The Bouguer gravity values then form the basis for studying planetary interiors. A primary question here is the degree to which isostatic compensation of planetary surface topography has occurred. The principle of isostasy requires that the internal mass of a planet rearrange itself to balance the topographic loads. It is well established that the continents and ocean basins of the Earth are in approximate

isostatic equilibrium. Studying the state of isostasy on other planets should help us understand basic processes that lead to this type of planetary equilibrium. The Bouguer gravity provides the fundamental information with which to study isostasy. For example, the Airy hypothesis adopts Archimedes' principle to explain a floating topography underlain by "roots" under the mountains and "antiroots" under the basins. The Airy hypothesis can be directly tested by comparing the gravity from a "root-antiroot" system to the Bouguer gravity. If isostasy is assumed, on the other hand, then one can search for density variations deep in a planetary interior to explain Bouguer gravity anomalies. Deep density variations may arise from convection currents or from density variations created in the original formation of the planet.

If analysis of the Bouguer gravity reveals that the topography is not completely compensated, then this topography must be supported by the elastic strength of the planetary interior or by the viscous stresses associated with solid-state flow. The longer the wavelength of the uncompensated topography, the deeper are the associated maximum stresses. Since the strength of a rock is directly relatable to temperature, it is possible to infer a maximum radial temperature profile consistent with the elastic support of the wavelength spectrum of uncompensated topography. If the temperatures so derived are unreasonably low, then it may be concluded that the viscous stresses associated with the convection at least partially support the topography.

To obtain detailed free-air gravity measures one should obtain simultaneous Doppler from three orbiting spacecraft along with relay link Doppler over two paths. These data allow the complete determination of the acceleration vector and thus makes all geophysical modeling a simple

static problem independent of orbital dynamics that plague all present reductions. The basic configuration is a relatively low altitude spacecraft (100 - 300 km) in a circular polar orbit with a two orbiting relay spacecraft at high altitude (5000 km) (one polar the other near equatorial). There should be a direct Doppler link between earth and each spacecraft and between the low polar orbiter and each relay spacecraft. All signals should be simultaneously acquired at one earth tracking station. The relay link Doppler could be placed on the relay's sideband depending on the transponder design. Oscillator stability should be 1 part in  $10^{11}$  over a 2 hour period, so 1-way systems may be applicable. These requirements could be placed on VOIR, Mars Rover and LPO missions, where complete global coverage is desired. In addition to the simultaneous acquisition of 5 Doppler counters for the orbiters, it may be necessary to acquire rover or lander tracking simultaneously for navigation and other science requirements. The present Viking configuration prohibits acquiring data from more than two spacecraft and as a result many radio science experiments are not obtaining the coverage they had requested.

### Giant Planets

The relationship between the interior of a giant planet and its gravity field is dominated by the effects of a rapid rotation rate. If the planet did not rotate and was fluid, it would take on a spherical shape under its own self-gravitation. For purposes of this discussion, tidal effects produced by the Sun and other bodies can be neglected, and as far as any gravity-sensing experiment is concerned, a nonrotating planet would appear essentially as a point mass. The external gravitational field would be spherical for all possible radial-density distributions, and it would be impossible to infer anything about the density



distribution from gravity data. However, because the planet rotates, its shape differs from a sphere, and the amount of the deviation from sphericity is reflected in the external gravitational field. It is probable that the rotation rates vary with latitude and with depth. In any case the amount of the deviation depends on the density distribution within the planet. For example, if the mass of the planet were completely concentrated at the center, then it would behave as a point mass and the measurements of the external gravitational field would yield a spherical structure. On the other hand, if the planet were homogeneous, the deviations from sphericity would be at a maximum, under the assumption that the density does not decrease with depth, and this maximum deviation would be evident in the gravity data. The actual situation for the giant planets can be expected to fall somewhere between the two extremes of total concentration at the center and a homogeneous distribution.

Close flybys of the giant planets at distances of 2 radii or less from the center may provide information on the second, third, and fourth zonal harmonic coefficients ( $J_2$ ,  $J_3$ ,  $J_4$ ) to an accuracy of one part in  $10^5$  or better. Jupiter Pioneer results to this accuracy have been used to test the assumption that the planet is in hydrostatic equilibrium, and to limit the class of plausible interior models. One of the most interesting features of the current Jupiter interior models is that they require several tens of earth masses of elements heavier than helium to fit the gravitational data, at least if the solar ratio of the abundance of helium to hydrogen is retained. In any case, it is clear that Jupiter is not of solar composition. By means of close flybys, we should similarly be able to determine the degree to which Saturn, Uranus, and Neptune deviate from solar composition. A comparison of the chemical

compositions of these four giant planets will yield new clues to the formation process for all of the planets.

### Satellites

Close flybys of the Galilean satellites and Titan, within 1000 km or so of their surfaces, will permit a determination of the second degree harmonics in their gravitational fields and hence a determination of differences in the principal moments of inertia to an accuracy at least an order of magnitude less than the expected size of the differences. With this information it will be possible to use the fact that the satellites respond to comparable perturbations from rotation and tides to discriminate very well between an ensemble of plausible interior models (Hubbard and Anderson, 1978). Because the rotational and tidal response are, to an excellent approximation, separately excited, it is feasible to deduce the degree of central condensation in the interior of the satellite in two independent ways from the two independent measurements of principal moment differences ( $B-A$  and  $C-(A+B)/2$ ), and hence to verify the assumption of hydrostatic equilibrium. This assumption is expected to hold for low density satellites, such as Ganymede, and if it does, then it will be possible to use the second degree harmonics as important boundary conditions on the interior models.

### Comets

A combination of radiometric data with on-board radar and accelerometers during a comet rendezvous mission can be used to determine the mass of the comet. A knowledge of the heliocentric positions of the comet and spacecraft from astrometric and radiometric data will allow a

determination of the solar tidal perturbative acceleration on the spacecraft with respect to the comet. Cometary drag accelerations and other non-gravitational accelerations on the spacecraft will be measured by on-board accelerometers. The total relative acceleration between the comet and spacecraft will be determined by subtracting the solar tidal and nongravitational accelerations from the total acceleration. Because the distance between the comet and spacecraft is known from the on-board radar, a determination of the gravitational attraction will yield a value for the mass of the comet. The goal of such an experiment is to measure the cometary mass to one percent.

#### References:

Sjogren, W. L., J. D. Anderson, R. J. Phillips, D. W. Trask, "Gravity Fields" IEEE Trans. on Geoscience Elec., GE-14, 172-183, 1976.

Hubbard, W. B. and J. D. Anderson, "Possible Flyby Measurements of Galilean Satellite Interior Structure," Icarus, 33, Feb, 1978.

## RADIO OCCULTATION

The radio occultation technique uses the measured signal amplitudes, phases, and polarization as a function of time. Studies of planetary atmospheres using radio occultation techniques began with Mariner 4 and have now been highly refined. In the case of bodies with thin atmospheres (such as Mercury, Mars, and Io), the amplitude data are used in conjunction with the ephemeris data primarily to determine the radius of the planet at the occultation points. For planets with denser atmospheres (such as Venus, Jupiter, and Saturn), the amplitude measurements may be used to determine the atmospheric microwave loss or the temperature and pressure as a function of altitude in the regions probed by the radio links and/or as an independent cross check on the frequency based results. The frequency measurements made during occultation experiments are utilized to determine the refractivity profiles in altitude for the regions probed by the radio link. The refractivity profile can in turn be used to determine the electron density distribution in the ionosphere and the temperature and pressure profiles in the lower atmosphere if the chemical composition is known. Amplitude and frequency fluctuations can be used to study turbulence and other local atmospheric structure. Faraday polarization rotation measurements at S-band can be used during Jupiter occultations, particularly polar ones, to measure the magnetic field close to the planet. Polarization during occultation might also be affected by rain in a planetary atmosphere. Basically, the following three items have the greatest influence on the accuracy of radio occultation results:

a) Stable on-board (auxiliary) oscillator

This is necessary to obtain useful data from the exit phases of planetary occultations (deep within the atmosphere) when a reliable uplink frequency reference is not available. This requirement is most important for Venus and the Outer Planets.

b) Precision-Steerable High-Gain Antenna

The high-gain antenna must be able to follow the refracted direction of the Earth in order to maximize penetration into the lower atmosphere for planets with dense atmospheres, such as Venus and the Outer Planets. It is necessary to keep the virtual earth at the peak of the antenna beam so that small position fluctuations caused by limit cycle, for example, do not produce large amplitude variations.

c) Knowledge of the local vertical direction

The precise knowledge of this parameter is necessary for accurate analysis of radio occultation data from Venus and the Outer Planets. It involves the precise measurement of the gravity field and rotation rate of a planet, as well as the local circulation velocities in a planetary atmosphere.

### Mercury

The primary objective for radio occultation at Mercury is to detect and characterize an intrinsic Mercurian ionosphere or a solar wind-magnetosphere interaction region, having very low electron densities (less than  $10^2$ - $10^3/\text{cm}^3$ .) A lower up or down link frequency coherent with the S-band down-link would be useful, along with the presence of another spacecraft in the vicinity of Mercury for the calibration of interplanetary electron fluctuations.

## Venus

On Venus, the most important radio occultation considerations are the precise measurements of frequency (phase) and power fluctuations as deep in the atmosphere as it is possible to measure before the critical refraction level is reached. These measurements are necessary to obtain accurate temperature-pressure profiles in the neutral atmosphere, absorptivity in the cloud regions, and characteristics of atmospheric turbulence.

To estimate the necessary oscillator stability and knowledge of the local vertical for accurate data analysis, the methods of Eshleman; and Hubbard et al., were applied. To an isothermal approximation, the error  $\Delta T$  in derived temperature,  $T$ , is related to the error factor,  $\delta$ , as follows

$$\frac{\Delta T}{T} \cong \frac{\epsilon D}{H} \delta$$

where

$\epsilon$  = refractive bending angle (rad)

$D$  = distance of spacecraft from limb at occultation (km)

$H$  = scale height (km)

In turn, the error factor,  $\delta$ , is related to the unmodeled oscillator drift rate,  $\Delta f'$ , by

$$\delta \cong \frac{\Delta f'}{f'}$$

$f'$  is the total frequency rate due to refraction, approximately equal to  $f V_n^2 / cD$ , where  $V_n$  is the projected (in the plane of the sky) spacecraft velocity normal to the planet's limb and  $c$  is the speed of light. The error factor,  $\delta$ , is also related to the uncertainty in the local

vertical,  $\Delta\alpha$ , by

$$\delta \cong 2\Delta\alpha\tan\theta$$

where  $\theta$  = angle between S/C velocity vector and vertical direction in a plane normal to the earth - S/C line of sight. For the purpose of a typical Venus computation

$D = 25,000$  km,  $\epsilon = 17^\circ$  (0.297 rad),  $H = 10$  km, and the characteristic time,  $\tau$ , of the measurement of 5 min (300 sec).

If the error in derived temperature is to be kept below 1% then  $\Delta T/T = 0.01$ , and  $\delta = 1.35 \times 10^{-5}$ . The corresponding one way frequency rate due to refraction,  $f'$ , is about 7.4 Hz/sec, and hence

$$\Delta f' \tau = \Delta f = 10^{-4} \times 300 = 3 \times 10^{-2} \text{ Hz}$$

and the stability of the oscillator must be

$$\frac{\Delta f}{f} = 1.3 \times 10^{-11}$$

It must be emphasized, that this is the required stability relative to a modeled part of the oscillator drift, i.e., the residual instability after removing a linear drift.

Although the gravity field of Venus has not been observed to display any asphericity, the sensitivity is so great that effects of planetary circulation may be important. For instance, for a 1% effect on the derived temperature, the direction of the local vertical must be known to a precision of

$$\Delta\alpha = \frac{\delta}{2\tan\theta} \cong 0.675 \times 10^{-5} \text{ rad} = 3.86 \times 10^{-4} \text{ deg.}$$

assuming, e.g., a representative value of  $\theta = 45^\circ$ . It must be pointed out that this great sensitivity only applies at the maximum penetration level, when the refractive bending is maximum. One may view this sensitivity to geometry inversely and note that it is possible that atmospheric circulation effects and very small departures from sphericity may be observable with the apoapsis occultations of Pioneer Venus, for example.

Relative to the oscillator stability constraints, a good example of inadequate stability was provided by the Mariner 10 oscillator, and in view of the absence of an ultra-stable oscillator on the Pioneer-Venus Orbiter it will be a fortunate accident if most of the exit occultation data will be useful for profile measurements.

In addition to those discussed above, an important requirement for Venus is the presence of a steerable high-gain antenna, capable of essentially tracking the refracted position of the earth along the limb. It is difficult to arrive at quantitative specification for the operation of this system. However, it is desirable that the post-facto knowledge of the gain of the antenna at any time during the occultation, at both S- and X-band frequencies, be better than 0.1 db (relative to its gain in the free-space position prior to the occultation). This has been very difficult to accomplish in the case of the Mariner 10 X-band data.

#### Mars

From the point of view of the stringency of geometrical factor in accuracy constraints on oscillator drift, Mars is the most amenable planet in the solar system. This is because of the very small refractive bending angles that are encountered. For the case of less than one percent error in temperature, and  $D = 10,000$  km,  $H = 10$  km,  $\epsilon = 0.011$  rad, the limit



on unmodeled oscillator instability is:

$$\frac{\Delta f}{f} \approx 4 \times 10^{-9}$$

and the allowable uncertainty in knowledge of the local vertical is

$$\Delta \alpha = 5 \times 10^{-3} \text{ rad} = 0.29 \text{ deg.}$$

(again for  $\theta = 45^\circ$ ).

Such an oscillator stability can be achieved with ordinary auxiliary oscillators. However, it should be pointed out that this figure applies to long-term ( $\sim 300$  sec) components of unmodeled drift, and rapid excursions in frequency of this magnitude would have influence on the shape of temperature profiles. Thus on-board oscillator stability remains an important parameter for one-way experiments.

Because of the small values of refractive bending, there is no necessity to have steerable antennas for Mars radio occultation experiments, unless surface reflection (bistatic radar) measurements are contemplated.

### The Outer Planets

The outer planets are discussed here together, because of certain similarities in their characteristics for radio occultation. They all have large diameters, deep atmospheres which cause at least moderate refractive bending before extinction due to absorption, relatively large fly-by distances and high spacecraft velocities during occultation. The radio occultation objectives for these planets are also similar, namely:

- a) Pressure and temperature profiles in neutral atmospheres
- b) Absorption and possibly depolarization in neutral atmospheres
- c) Turbulence and other local structure in the atmosphere
- d) Magnetic field measurements using Faraday Rotation techniques
- e) Ionospheric electron density profiles and characteristic ionospheric turbulence

The last objective is made more difficult by the large fly-by distances coupled with high electron density gradients in the lower ionosphere (if the other outer planets have ionospheres similar to the one found on Jupiter by Pioneers 10 and 11). This causes the spacecraft trajectory to lie beyond the caustics, which leads to difficulties in the data analysis due to multipath.

The values of  $\Delta f/f$  and  $\Delta\alpha$  required for the outer planets are shown in Table I, along with the values for the other planets, in each case assuming  $\theta = 45^\circ$ . They were computed assuming  $D = 10 R_{\text{planet}}$ ,  $\epsilon = 0.01$  to  $0.1$  (the angle of  $0.01$  was not exceeded for Pioneers 10 and 11 before absorption and possibly turbulence extinguished the signal; deeper penetration, however, may be possible at the other planets),  $H = 20, 40, 45$  and  $25$  km for Jupiter, Saturn, Uranus and Neptune, respectively, assuming temperatures of  $200, 170, 150$  and  $130^\circ\text{K}$ .

The resulting stability limits lie between  $9.3 \times 10^{-11}$  for Uranus with  $\epsilon = 0.01$  to  $1.6 \times 10^{-12}$  for Jupiter with  $\epsilon = 0.1$ . These limits, although stringent when compared to present-day unstabilized auxiliary oscillators, are well within the capabilities of the temperature-controlled ultra-stable oscillators to be used for Voyager and, hopefully, for all missions beyond Pioneer-Venus. (The stability of the Voyager USO, as

reported by G. Wood in a private communication is  $1.5-2.08 \times 10^{-12}$  relative to a linear fit). The corresponding figure for the Pioneer 10 and 11 oscillators was about  $5 \times 10^{-10}$  which, while adequate for gross features of the atmosphere, leaves much to be desired for accurate detailed temperature structure and precision at high altitudes.

The situation relative to the local vertical uncertainties is not quite as satisfactory. Although the general shape of the planet can be very well determined from the measured gravity field and rotation, the effects of planetary general circulation (differential rotation) are not well known and could have serious effects upon the derived results (Hubbard et al., 1975). For instance, differential rotation between the zones and belts on Jupiter can introduce deviations in the local vertical of up to  $5 \times 10^{-3}$  rad. This is more than two orders of magnitude higher than the allowable uncertainty of  $1.4 \times 10^{-5}$  rad. for  $\sigma = 0.01$ , and such an error, if not correctable, would invalidate profile data in the lower atmosphere. The situation is analogous for the other planets, especially if penetration to lower levels than those probed on Jupiter should be possible, in which case a knowledge of the local vertical to an accuracy of  $10^{-6}$  to  $10^{-5}$  rad. is required for accurate data analysis.

Since it is doubtful that such accurate determination of planetary circulation can be made from imaging observations, it is possible that vertical occultations (those for which the projected velocity vector is along the local vertical) will be necessary to obtain good radio occultation data for atmospheric profiles of the outer planets. Conversely, if the atmospheric refractivity profiles are known from probe

measurements, non-vertical occultations can be used to study deviations of the local vertical from the gravity normal in planetary atmospheres.

#### E. Satellites

Satellite occultations, with the exception of Titan, are likely to impose the same sort of requirements as Mercury, i.e., a lower frequency to measure tenuous electron density distributions. For Titan, the oscillator stability limit is probably somewhere between those for Mars and Uranus, and any oscillator designed to be adequate for the outer planets will also be adequate for Titan.

#### F. Comets

For radio occultation experiments during cometary fly-bys, one can expect to be able to achieve an occultation by the tail and possibly the coma, but probably not the head or nucleus. For this reason, the ability to measure low electron concentrations will be desirable, indicating the use of a lower coherent frequency and two-spacecraft calibration of interplanetary electron fluctuations. A passage behind the nucleus would be very useful for size measurements and determination of possible effects of particulate matter near the solid core.

TABLE I-1

Parameters Important to Radio Occultation Accuracy

Planet	Limb. Dist. D (km)	Scale Ht. H (km)	Refr. Ang. $\epsilon$ (rad)	Local Vertical Uncertainty Limit (Rad)	Unmodelled Oscillator Drift Limit ( $\Delta f/f$ )
Mercury	N.A.	N.A.	N.A.	N.A.	Nominal
Venus	25,000	10	0.297	$0.7 \times 10^{-5}$	$1.3 \times 10^{-11}$
Mars	10,000	10	0.001	$5.0 \times 10^{-3}$	$4.0 \times 10^{-9}$
Jupiter	700,000	20	0.01 0.1	$1.4 \times 10^{-5}$ $1.4 \times 10^{-6}$	$1.6 \times 10^{-11}$ $1.6 \times 10^{-12}$
Saturn	600,000	40	0.01 0.1	$3.3 \times 10^{-5}$ $3.3 \times 10^{-6}$	$2.1 \times 10^{-11}$ $2.1 \times 10^{-12}$
Uranus	240,000	45	0.01 0.1	$1 \times 10^{-4}$ $1 \times 10^{-5}$	$9.3 \times 10^{-11}$ $9.3 \times 10^{-12}$
Neptune	220,000	25	0.01 0.1	$5.7 \times 10^{-5}$ $5.7 \times 10^{-6}$	$6.0 \times 10^{-11}$ $6.0 \times 10^{-12}$
Satellites	-	lower frequency and two S/C calibration desirable			
Comets	-	same as Satellites			

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## SURFACE SCATTERING

Scattering of radio waves from planetary surfaces allows determination of two primary quantities: reflectivity of the surface material and roughness of its uppermost parts. Measurement of reflectivity may be used to infer dielectric constant of the material; from that one may infer the density. Roughness of the surface is obtained by inverting the dispersion of the echo (in either time or frequency). Both density and roughness are of interest from an engineering point of view (as they apply to landing vehicles); they are also useful as inputs to geologic models of surface structure.

Accurate amplitude measurements of a reflected signal are necessary to obtain planetary reflectivity. Errors of 1 dB in total received power result in dielectric constant estimate errors of 14% for typical values. These then propagate to 17% errors in density when applying accepted models (Gold et al., 1970). Though the density error may not appear large in absolute terms, the geologic interpretation (based on particle size, origin, etc.) may change quite dramatically.

Surface scattering, in general, arises from the entire planet. Those parts of the surface far from the specular region contribute only weakly, however, and are sometimes lost in the noise. With current spacecraft antenna design, such areas may also be underilluminated as a result of narrow antenna beamwidths. When beam patterns are known in both azimuth and zenith angle, post-experiment processing can be used to compensate for the underillumination. In the case of very rough surfaces, however, the beamwidth may be so narrow as to mask

points of inflection on the scattering curve and permit only a lower bound estimate for the surface roughness.

Rather than track the specular reflection region, one may select a point target on the surface for study. In this case the antenna is directed toward the target in such a way that the radio photometric function can be derived. Here a narrow beamwidth may be an advantage, since echo from regions surrounding the target can be suppressed by antenna directivity. In either case, accurate pointing is required in order that the target not drift out of the beam; good reconstruction of antenna performance during the experiment is necessary for later analysis, including compensation for pointing errors when and if they did occur. Tolerances of 1/10th beamwidth have been used in the past; spacecraft beamwidths of  $20^\circ$  would be desirable to obtain high angle scattering behavior during specular point tracking.

The frequencies used for surface scattering experiments determine the sizes of the structure sensed -- shorter wavelengths respond to smaller scale roughness. As technology has advanced, operating frequencies for spacecraft communication have increased and this scale size has decreased. For X-band we believe that structure between about 3 cm and 30 meters is responsible for most of the scattering, with about 5 meters being an "effective" scale size for the averaged result (Tyler et al., 1971). Thus, X-band scattering results would be expected to be quite appropriate for lander/rover engineering studies of the surface.

The move to higher frequencies and shorter scale sizes is accompanied by greater demands in data acquisition and processing. A uniform



roughness over some range of operating frequencies leads to a linear increase in the signal bandwidth which must be processed. In fact, the roughness appears to increase as a fractional power of the frequency (because smaller structure is being sensed) so the effect is more than one-to-one (Parker et al., 1973). The move to higher frequencies also means more directive antennas and (for the simpler types of scattering experiments) under-illumination of the target area, as discussed above.

Dual-frequency operation, such as with S- and X-band, permits one to study the roughness on two different scales. To guarantee that the same physical surface is responsible for the echo received, operation at the two frequencies should occur simultaneously.

The echo received after scattering by the planetary surface will be spread over a range of frequencies. Closed-loop receiving systems are inappropriate for these types of operations and all data must be recorded from open-loop receivers. Bandwidths required depend on many factors, the most important of which is spacecraft-to-target velocity. Typical experiments could result in received signals having bandwidths of a few tens of hertz to several tens of kilohertz; in some cases the center frequency may drift considerably with respect to the bandwidth.

Telemetry sidetones have the potential for causing interference with the desired echo signal. The position and spacing of sidetones and their interference potential depends on the experimental geometry. A simple solution is to turn off as much of the telemetry as possible during bistatic radar operations; if the remaining sidetones are several

tens of kilohertz from the carrier, it is unlikely that interference would be a major problem.

For scattering experiments, oscillator stability by present standards is not a constraint. The scattered signal is broadened and shifted by amounts discussed above. So long as the oscillator does not drift appreciably with respect to these limits, no experimental problems are likely to arise. The possibility of an analysis using synthetic aperture techniques would require that the transmitter and receiver have very stable frequencies; no such experiment has been proposed, however.

Depolarization studies have not progressed far with bistatic radar; some results on unpolarized vs polarized echo power have been reported by Tyler and Howard (Tyler and Howard, 1973). Earth-based studies of Mars (Downs et al., 1975) suggest that 20 dB isolation between circular polarizations may be needed for proper study of depolarization of that planet.

The oblique nature of most bistatic-radar scattering studies necessitates the reception of both polarizations of a scattered signal. Near the Brewster angle equal powers return in each circular component so that a simple 3 dB in total signal power is lost when only one polarization is received. Studies with both circulars are also useful in identifying the Brewster angle itself. The capability to transmit orthogonal linear polarizations from the spacecraft would be of great benefit in this respect since the vertically polarized component incident on the surface gives rise to no first-order scattered signal at the Brewster angle itself. Detection of this null with linear polarizations would be easier than with circulars, but overall, circular polarization is preferred.

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## SCATTERING FROM PLANETARY RINGS

Planetary rings when encountered by a spacecraft in a fly-by trajectory affect the amplitude, phase, and power spectrum of a radio signal transmitted from the spacecraft to Earth. These effects when studied as a function of geometry, wavelength, and polarization yield information concerning particle size, shape, orientation, material, number density, and radial structure. Such information is valuable in studying the origin and evolution of planetary rings.

The wave that propagates straight through the rings is coherent with the incident wave. The amplitude and phase of both the copolarized (CP) and crosspolarized (XP) received waves are measurable parameters. Transmission of two orthogonal linear polarizations from the spacecraft with simultaneous measurement of the CP and XP components on the ground is required to allow a full construction of a weighted forward scattering matrix. Symmetry properties of this matrix reveal the existence of any orderly orientation of the particles. Simultaneous measurement at two or more coherent wavelengths is very useful in identifying the effective particle size. For example, dispersive measurements at S- and X-bands are quite sensitive to the size of ice particles with effective radius in the 0.5 - 10 cm range.

The phase of the coherent signal is actually measured as an additional shift in the carrier frequency. If two adjacent incident rays undergo differential phase change through the rings, the wavefront of the exciting wave will be slightly bent causing a doppler shift of the received signal, much in the same way as atmospheric ray-bending. A closed-loop receiver tracking the frequency of the coherent signal

yields the doppler history which when integrated gives the phase information.

The precision of a coherent phase measurement is determined by the frequency stability of the spacecraft oscillator over the measurement integration time. If  $\delta$  is the fractional change in oscillator frequency,  $f$ , over integration time,  $T$ , then the smallest detectable phase change  $\Delta\phi$  over a small radial distance  $\Delta r = V \cdot T$  is  $\Delta\phi/\Delta r = (\delta \cdot f/V)$ , where  $V$  is the spacecraft velocity projected along the radial line. For single scattering conditions  $\phi$  is directly proportional to the particle areal density,  $n$ , and hence the smallest detectable gradient  $\Delta n/\Delta r$  is directly proportional to  $\delta$ .

The main error in estimating the coherent signal amplitude is due to pointing accuracies of the spacecraft antenna, with the error for X-band more critical because of the very narrow antenna beam. For the Voyager mission accuracy is limited to about 10% at X-band and 1% at S-band (Eshleman et al., 1977).

Unlike for atmospheric measurements, the closed-loop receiver will probably be tracking the coherent signal received mixed with a possible strong wide-band incoherent component. The receiver must be optimized for operation under such conditions.

Power lost from the incident coherent wave is scattered incoherently in all directions. The Keplerian motion of the particles and the motion of the spacecraft cause the received incoherent signal to spread in frequency. For example, during the JST Voyager clear-rings occultation period the frequency spread may reach 6 kHz, if particles in the

centimeter-meter size range are dominant. For transmission at two orthogonal linear polarizations, the wide-band open-loop receiver can, therefore, be used to record both the CP and XP components of the incoherent signal. The coherency matrix can then be constructed as a function of time. Symmetry properties of the coherency matrix reveal information about the shape and orientation of the particles. Spectral processing of the coherency matrix elements yields power spectra which, for optimized trajectories, can be directly related to the radial structure of the rings. The accuracy of the inversion of the incoherent signal spectra is primarily determined by the signal-to-noise ratio at the receiver.

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## II. B. SOLAR PLASMA, GRAVITATIONAL PHYSICS, MAGNETISM, AND GRAVITY WAVES

### THE CORONA, THE SOLAR WIND AND MAGNETIC FIELD AND COMET INTERACTIONS

Earth and the other planets of our solar system are immersed in streaming, irregular plasma generated by the sun which is thought to have profound effects on our environment. The fortunate circumstance which makes life on earth possible and, perhaps, unique is the earth's magnetic field which produces the protective barrier, or bottle, in which we live. This magnetic field, while quantitatively known, is produced by totally unknown means.

The sun's atmosphere extends into interplanetary space because it is so hot. This extended atmosphere is referred to as the corona very near the sun ( $r \leq 5 R_{\odot}$ ) and as the solar wind as it flows supersonically outward at greater distances. The heat source for the corona is not well-understood, but is thought to be energy transported from the convection zone by mechanical (sound) waves having periods on the order of 300 seconds. Further measurements of both the average density and the density fluctuations as a function of distance from the sun, especially very near the sun, will help in improving this understanding. Radiometric data from spacecraft are a unique source of such measurements. Refinements in radiometric techniques can greatly enhance the usefulness of the measurements.

## Steady State Corona

Many optical earth-based experiments have been conducted during solar eclipses in order to determine a model of the steady state coronal electron density distribution. The model commonly used to describe the electron distribution is static and spherically symmetric and referred to as the Baumbach-Allen interpolation formula

$$N_e(r) = \frac{A}{r^6} + \frac{B}{r^{2+\epsilon}}$$

where  $A$ ,  $B$ ,  $\epsilon$ , are coefficients to be determined from the data analysis, and  $r$  is the radial distance from the sun. Experiments to investigate this model have been conducted optically during solar eclipses for many years and at radio frequencies by measuring the bending of radiowaves from natural sources and spacecraft. More recently several spacecraft have provided a unique opportunity to conduct similar experiments based upon the group retardation of a ranging signal transmitted to and from the spacecraft at a single frequency or at two frequencies simultaneously (Muhleman et al., 1977; Tyler et al., 1977). Under such circumstances the signal exhibits a time-delay given by

$$\Delta t_g = \int_{\text{path}} \frac{ds}{V_g} \propto \frac{1}{\omega^2} \int N_e(s) ds$$

where;

$$N_g^2 = 1 + \frac{e^2}{m\epsilon_0\omega^2} N_e = \left(\frac{c}{V_g}\right)^2$$

where  $N_g$  and  $V_g$  are the group index of refraction and group speed respectively. It is evident that the group-delay is directly proportional to the integrated electron density along the ray path and inversely proportional to the frequency squared. Thus, spacecraft dual frequency radiometric data are a unique source for high accuracy determination of the parameters of this simple model.



However, the model itself is in need of sophistication. This can be accomplished by adding solar latitude terms, and perhaps time variation as well. Thus, the purpose of this analysis is to deduce coronal electron density models for a wide range of solar geometries and over the solar cycle. In addition, this analysis should provide an averaged integrated electron density along a raypath and thus interface directly with the analysis of variations in columnar electron densities. Analysis of the data for properties of long term solar events, such as solar streamers, coronal holes, etc., appears feasible. Finally, the electron density profile may couple with the evaluation of other more physical properties of the solar corona.

### Solar Wind Fluctuations

In order to have a complete understanding of the solar wind we must learn more about the temporal and spatial distribution of wave energy as well as the average properties of the solar wind. One would like to understand the fluctuations in the solar wind: What is their relationship to the average solar wind? How are they related to the sun or features in the lower corona? What is their amplitude and frequency distribution with heliocentric distance? How do the fluctuations and average properties vary during the 11 year sunspot cycle, the earth's putative 22-year weather cycle, and the long term increases and decreases in solar output? Unique new information which will help in answering these questions can be obtained from radio metric data of improved quality. The two major improvements required are longer continuous records and reduced noise on the data measuring the change in columnar content.

We wish to study the power spectrum of solar wind fluctuations at a function of time and of the distance of the ray path from the sun. The power spectrum gives the rms fluctuation on a given time scale. To study a broad range of frequencies one needs long records of the columnar content (change) sampled frequently, but with the noise on each point being as low as possible. If one is dealing with dual-frequency Doppler data, one needs assurance that there are essentially no cycle slips in either channel. For DRVID data the equipment drifts during a pass must be small. For range data, which measures the total columnar content, the absolute system calibration and its variation with communication parameters must be known to good accuracy. To relate changes in the columnar content to features on the sun one needs round trip data on which to perform autocorrelation analysis. Round trip data also may give an indication of the solar wind velocity distribution through the power spectrum (Callahan, 1974).

From radiometric tracking data one can investigate the power spectrum of the solar wind in the frequency range  $1/0.2T \leq \nu \leq 1/2\Delta t$ , where  $T$  is the length of the record and  $\Delta t$  is the sampling rate. Thus, one needs long passes ( $T \geq 12$  hours) and fast sample rates ( $\Delta t < 1$  min.,  $\sim 10$  sec.) in order to investigate a useful range of frequencies. The parameters specified give  $1 \times 10^{-4} \leq \nu \leq 8 \times 10^{-3}$ ,  $5 \times 10^{-2}$  Hz. Ultimately, continuous records as long as a solar rotational period will be desirable.

The power density of the columnar content for ray paths at  $\sim 0.15$  AU ( $32R_{\odot}$ ) from the sun was found to be  $P(\nu) = 4.4 \times 10^{+20} \nu^{-2.9} \text{ cm}^{-4} \text{ Hz}^{-1}$  from Mariner 6, 7, and 9 DRVID data (Callahan, 1975). To fully utilize the frequency range above requires (1) drifts, cycle slips, etc. during

a pass be less than 1 meter of two-way S-band range change and (2) total noise per point be less than 0.01 meter. Increased noise reduces the highest frequency available to  $\sim 5 \times 10^{-2} \sqrt{N/0.01}$  Hz, where N is the noise in meters. Larger drift rates cannot be tolerated in obtaining data on the low frequency structure of the solar wind. Round trip data of the specified quality and duration would allow autocorrelation analysis to detect plasma streams crossing ray paths to spacecraft out to 5 AU. Simulations of the autocorrelation technique are being planned in order to fully explore the noise requirements.

Data are needed over a range of SEP (sun-earth-probe) angles, from the smallest at which data can be obtained ( $\sim 0.5^\circ$ ) to at least  $35^\circ$  in order to investigate the radial dependence of the fluctuation spectrum. The communication system must be designed and calibrated so that no additional unknown equipment effects occur in near-sun tracking and there is a reasonable probability of obtaining data on any given day for SEP angles  $\geq 1^\circ$ .

If data of the quality specified above are obtained from more than 1 station per day so that the records are (nearly) continuous, or if measurements of  $\sim 1\text{m}$  accuracy of the total columnar content are obtained during each pass, it becomes possible to study the large scale ( $\sim 2-7$  day) changes of the solar wind. This density structure is known to be related to magnetic sectors, but further data are required to link the density to surface features and to study the turbulence within the large scale structures. Continuous data would allow improved separation of radial and temporal effects. It would be possible to study the effect of flares on the solar wind structure. In addition to investigating temporal effects on a time scale of a few days, it is of interest, and could be

of importance for understanding climatic trends since the solar wind is known to affect the earth's magnetic field, to determine the average solar wind properties and the fluctuation spectrum over the sunspot cycle. Thus, the data specified above should be collected from all possible missions and be included in any future plans for radio science. These data would be especially useful if obtained from more than one spacecraft at a time in different solar geometries.

#### Magnetic Field Interactions

The sun and Jupiter are prime candidates for studying plasma-magnetic field interactions. The combination of two-frequency ranging and the ability to measure signal polarization at S-band would make it possible to measure the magnetic field strength deep in the corona and deep in the atmosphere, over the poles of Jupiter.

#### Comet Interactions

Columnar content data and especially fluctuations in the content make it possible to investigate some properties of comets and their interaction with the solar wind. The cometary ionosphere causes 1-2 m of S-band range change. It is likely that fluctuations in this value would be large ( $\sim 0.1$ m) on time scales of seconds. More rarefied regions of the comet where it interacts with the solar wind may contribute range changes of  $\sim 0.1$ m, again on time scales of seconds to minutes. Dual frequency data need to have resolution of  $\sim 0.01$ m on time scales of 0.1-1 sec to resolve these changes. Polarization data to determine the fate of the solar wind magnetic field would also be useful. Measurement of the attenuation by solid particles is probably not possible.

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## GRAVITATIONAL PHYSICS

Since the advent of special relativity in 1905, it has been recognized that Newtonian gravitation cannot be a complete description of the gravitational interaction. Progress in experimental relativity and gravitation is closely tied to advances in technology and the discovery of new astrophysical phenomena. Even though there are other formidable difficulties in carrying out measurements of relativistic gravitational effects, they are of profound importance both as they allude to the description of the physics in strong gravitational fields which may be encountered in astrophysics and cosmology and, in the deepest sense, as they further our understanding of one of the fundamental physical interactions of nature.

Extremely strong gravitational fields are important in astrophysics and in studies of the early history of the universe. In some cases such as black holes, the gravitational potential energy is believed to be comparable with the rest energy of the systems considered. The presently accepted theory of gravitation, General Relativity, may be incorrect in this limit. However, the differences of its predictions from those of Newtonian theory have been tested so far only in the weak field limit and to about 1% accuracy.

Greatly improved accuracy is possible without stretching the present state of technology. Measurement of the vacuum-equivalent range from tracking station to spacecraft with errors of only a few centimeters is now feasible. With dual-frequency, say S- and X-band, uplinks and downlinks the plasma contribution to the apparent range can be deduced. For signals that pass near the sun a third frequency would be necessary to account for scattering whose effect on delay behaves as  $f^{-4}$ .

However, to interpret such range measurements at a comparable level of accuracy requires planetary landers or really drag-free spacecraft. Ordinary spacecraft in heliocentric orbit are buffeted unpredictably by non-gravitational forces to such an extent that the accuracy of interpretation of these measurements would be degraded by up to four or five orders of magnitude. Planetary orbiters represent an intermediate class of spacecraft: the possibility for frequent "calibration" of their orbits with respect to a planet, whose non-gravitational accelerations are very small, prevents a large buildup of errors in the determination of the orbit of the orbiter.

A Lander with such a ranging system on either Mercury or Mars, if usable for several years, could allow up to three or four orders of magnitude improvement in tests of several aspects of post-Newtonian gravitation theory such as: (i) the fundamental principle of equivalence for massive bodies; (ii) the direct effect of solar gravity on light propagation; (iii) the post-Newtonian orbital motions of planets; (iv) possible "preferred-frame" effects; and (v) a possible time variation of the gravitational constant.

A drag-free spacecraft with an atomic clock on board, with a frequency stability of better than 1 part in  $10^{14}$  over time scales longer than a few seconds, would allow a test of the so-called second-order redshift if the spacecraft approached to within a few solar radii of the sun. In addition such a spacecraft, or a Mercury orbiter or lander, would allow a determination of the (dimensionless) coefficient,  $J_2$ , of the second harmonic of the sun's gravitational field with an uncertainty of under  $1 \times 10^{-7}$ . An accurate determination of  $J_2$  is essential, for example for the proper interpretation of the perihelion advance of Mercury's orbit in terms of the non-Newtonian, or relativistic, part.

Even without the full advantages of present technology, substantial advances can be made in probing the fundamental attributes of gravitation. In fact, all relevant solar-system measurements need be combined to allow the most stringent conclusions to be drawn.

In its recommendation to NASA, the Subpanel for Relativity and Gravitation put this matter especially well:

"Precision measurement of the dynamics of the objects in the solar system and observation of the behavior of electromagnetic waves in the gravitational field of the Sun is, in our opinion, the single most important program to advance the understanding of relativistic gravitation. As the natural time scales are of the order of planetary orbital periods, the program by its very nature is a long term effort; no single measurement or unique mission can provide the complete description needed. Precision range, angular, and timing data evolved over a matter of decades will constitute a rich legacy to natural science provided by the space program.

A rational program is multifaceted and should include:

- 1) Vigorous and continuing support of radar ranging to the planets and the laser ranging experiments to the moon.
- 2) The development of a dual-frequency NASA transponder with 10 cm ranging capability and its utilization on all planetary orbiter and lander missions as well as the upgrading of NASA tracking facilities for dual-frequency reception and transmission.
- 3) Allocation of enough time and budget for data acquisition to utilize fully ranging data from planetary orbiters and landers even after the prime objectives of the mission in other disciplines have been accomplished.
- 4) The strong support of data analysis, preferably involving two independent groups."



## GRAVITATIONAL WAVES

A gravitational wave pulse or train is a transverse spatial strain propagating at the speed of light. Its effect on matter is to produce a time varying change of distance between separated masses. Gravitational radiation is now being sought by a variety of resonant or broadband experimental techniques, in different wavelength bands. Methods proposed for detection include observing the fringe shifts produced in a Michelson interferometer, monitoring the Doppler frequency shift of an electromagnetic signal exchanged between two or more free bodies, and measuring the resonant stresses excited in a single massive body. Various astrophysical objects could be sources of such pulses, or of incident wave trains. Double stars, supernovae, quasars, pulsars, and black holes all should emit gravitational radiation at some level. At present, calculation of the intensities and frequencies of occurrence of the strongest possible sources is very uncertain. What is sure is the high scientific importance of any successful observation of such radiation, and of the consequent "gravitational wave astronomy" thus made possible (Thorne and Braginsky, 1976).

High precision Doppler tracking data will in general show three pulses in response to each sufficiently intense pulse of gravitational radiation incident on the solar system (Estabrook and Wahlquist, 1975). The DSN capability for observing the strains of gravitational radiation is non-resonant, and most sensitive in the very long wavelength band (periods from 5 sec to 3000 sec). The low frequency edge of this response--corresponding to perhaps a 3000 second period--is set by the consideration that the 3 pulses to be observed must be separated by the round-trip-light-time (RTLT) to a remote Doppler transponder. Missions to Mars and beyond have RTLT's of this order. The high frequency limit of response--at

perhaps 5 second period--is set by the increase, with frequency, of interfering receiver phase noise and interplanetary plasma scintillations, and by the poorer stability of timekeeping standards (Estabrook and Wahlquist, 1977; Wahlquist, Anderson, Estabrook and Thorne, 1977).

The radio science system requirements to make possible high precision Doppler observations of gravitational radiation are, first, that all competing phase fluctuations in the very long wavelength band be kept at a minimum for selected extended tracking passes of interplanetary missions--passes long compared to a RTLT. This minimum, as a practical matter, is set by the station timekeeping standard. The best fractional frequency fluctuation (to be precise, the root Allan variance  $\sigma_y(2, \tau, \tau)$ , where  $y = \Delta v/v_0$ ,  $v_0$  is the carrier frequency) attainable with H-maser timekeeping is somewhat worse than  $10^{-15}$  --perhaps  $3 \times 10^{-15}$  -- from 30 sec to 3000 sec averaging times  $\tau$ . So that this is not significantly degraded, a comparable fractional frequency fluctuation upper limit must be required of all other elements of the Doppler tracking system: station cabling and timing electronics; transmitter, transponder, and receiver elements; Doppler resolver and readout. A proposed precise statement of this requirement in terms of a measure of phase fluctuation, viz.,  $\overline{\Delta\phi} \equiv 360 v_0 \tau \sigma_y$  degrees, is that for X-band  $\overline{\Delta\phi} \leq 0.1^\circ$  for  $5 \text{ sec} \leq \tau \leq 30 \text{ sec}$ , and  $\overline{\Delta\phi} \leq 0.1^\circ (\tau/30)$  for  $\tau \geq 30 \text{ sec}$ .

The second radio science system requirement is equally important, and similarly motivated. Measurements and calculations of the fractional frequency fluctuation due to solar wind inhomogeneities show that, even during solar quiet times and when tracking spacecraft in antisolar directions, the plasma noise at S-band exceeds the above limits by perhaps a

factor of 10-100. Round-trip X-band should show solar plasma fractional frequency fluctuation reduced from this by a factor of 16. Radio science gravitational wave experimenters on future interplanetary projects will require coherent X-band uplink and downlink Doppler tracking, coupled with S-X or perhaps X-K dual-frequency links for separation of remaining plasma noise from other Doppler signals (Anderson and Estabrook, 1978). Accordingly, it will be necessary to implement a ground transmit capability for X-band Doppler, and receive capability for K-band, again with system noise less than that of the hydrogen maser timekeeping. This approach reduces the plasma phase noise problem by going to higher radio frequencies. A complementary method is to measure the phase noise by transmitting simultaneously from the spacecraft at a lower frequency, e.g., S or L band, and "calibrating out" the interplanetary medium. A combination of the two approaches may be optimum.

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### III. FUNCTIONAL AND DETAILED PERFORMANCE

This section specifies the functions which must be performed and the flow of information required to produce complete Radioscience data products. Since there is overlap with navigation requirements as specified in JPL Document 900-745 (Multimission Planetary Tracking System Requirements), it should be noted that the Radio Science requirements cover more spacecraft and ground data types and further specify certain real time displays which are necessary to insure data quality. A block diagram of the overall system is shown in Figs. III-1, 2, and 3.

The individual blocks of the system are discussed in the following text along with a table of functional capabilities and deliverables for each element. Content and format documentation are also listed. The final table of this section contains detailed performance specifications for the system and allocations among the elements where appropriate.

#### References (all are JPL internal documents)

- 618-638 Software Requirements Document/Software Planning Document - Part 1 Trajectory Analysis Subsystem
- 820-13 Deep Space Network System Requirements - Detailed Interface Design (Modules of specific interest are RSC 11-1,3; IDR 12-1,2; Track 2-12 and Track 2-14)
- 820-14 Deep Space Network Requirements - Subsystem Interface Design
- 821-8 Deep Space Network System Requirements - Deep Space Network Radio Science System 1978 through 1983
- 824-17 Deep Space Station Subsystem Requirements - CTA 21 Radio Science Subsystem 1978 through 1983
- 824-18 Deep Space Station Subsystem Requirements - Deep Space Station Radio Science Subsystem 1978 through 1983
- 900-772 User Tracking Data File Interface Document

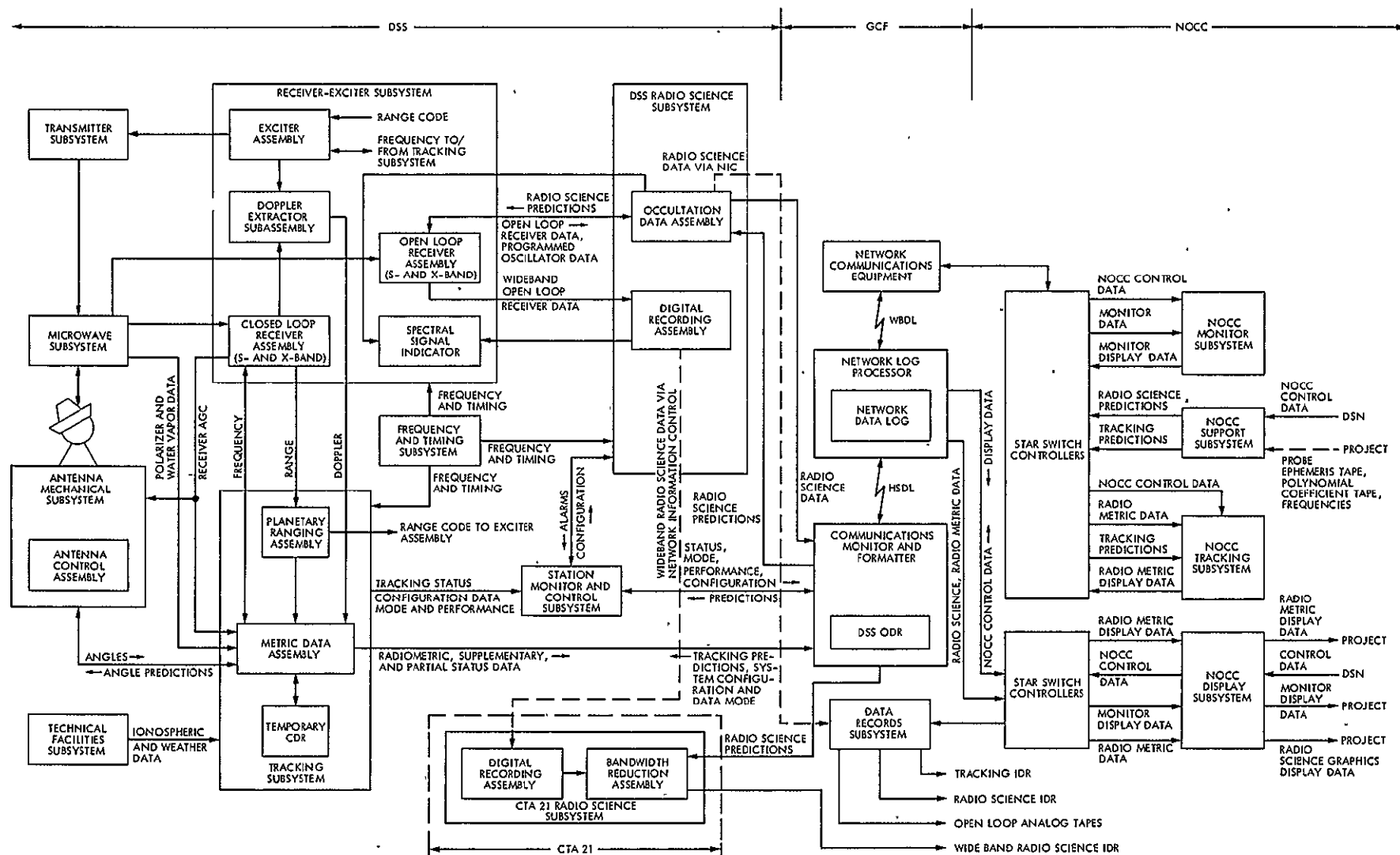


Fig. III-1. DSN Radio Science System Mark III-78 Functional Block Diagram

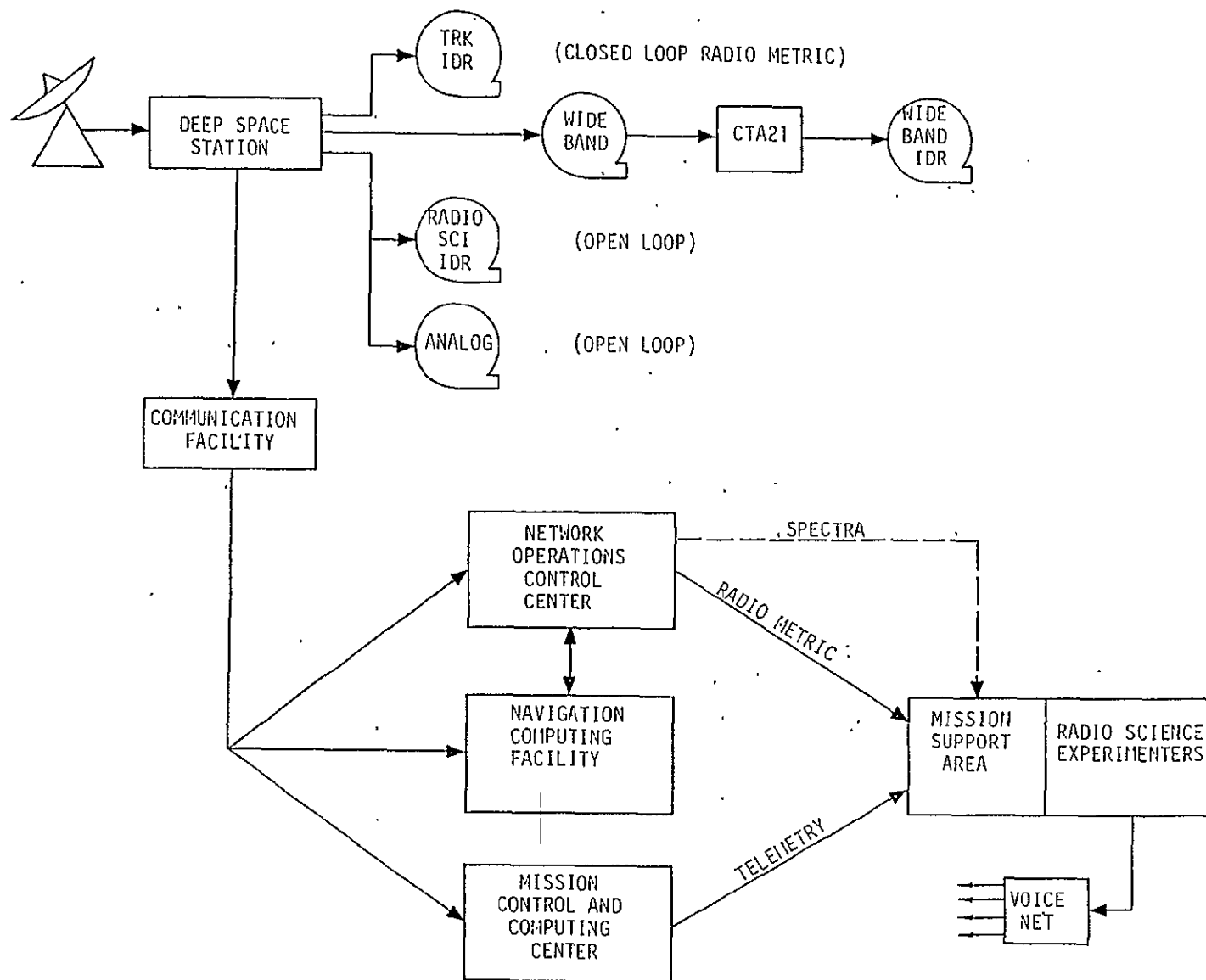


Fig. III-2. Real-Time Processing

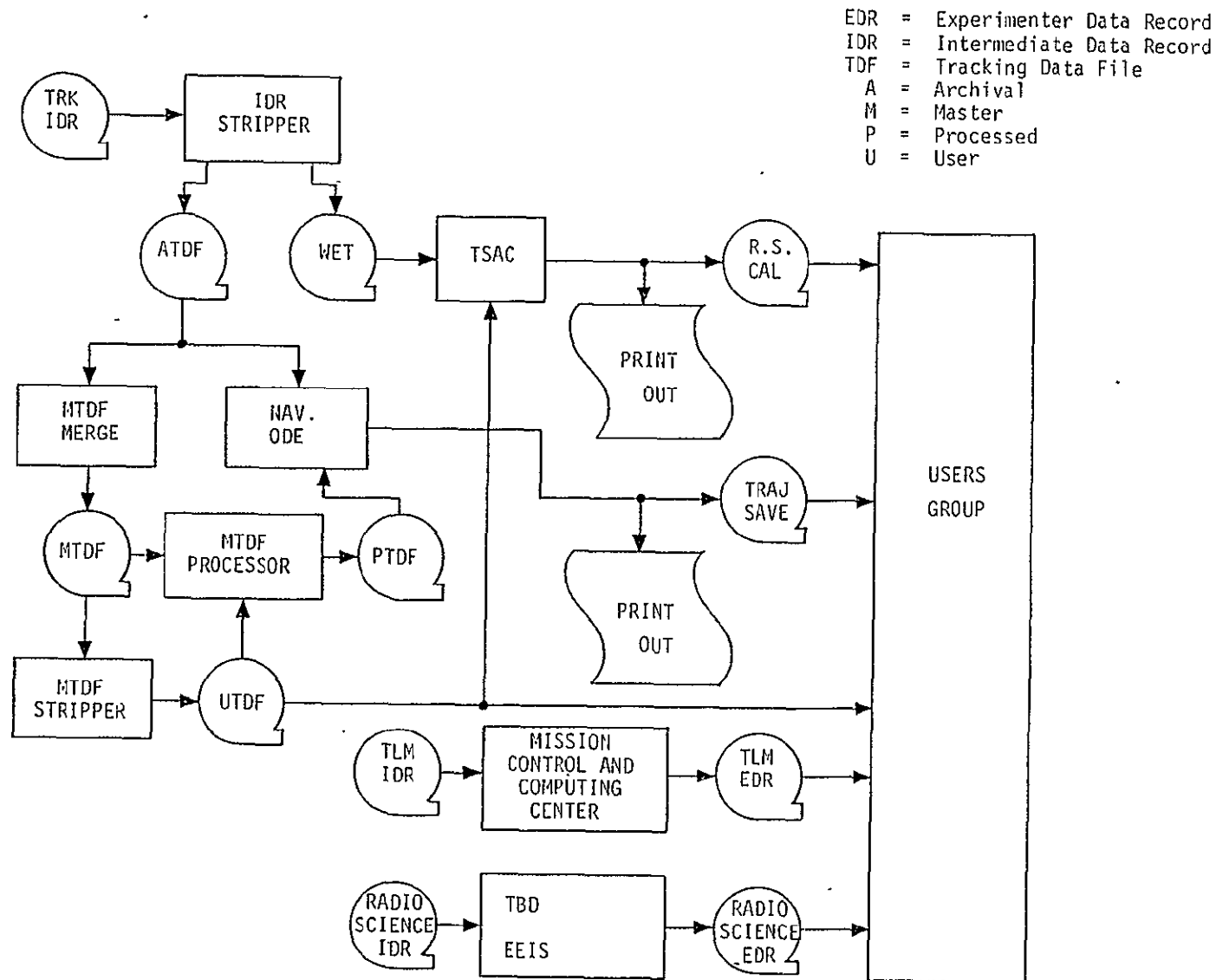


Fig. III-3. Non-Real-Time Processing

### Table III-1. Spacecraft Functional Requirements

The spacecraft capabilities presented reflect scientific experiment possibilities for missions envisioned through 1988. With the exception of the linear S-band polarization and X-band receive capability required for the Jupiter missions, and perhaps others, the capabilities are currently in existence. Further, the NASA standard transponder has several features which will permit new types of experiments if they are proposed in the future.

#### TABLE III-1

#### SPACECRAFT

##### Equipment:

##### NASA STD TRANSPONDER

S receive (X receive on selected future missions)

S & X (11/3)S coherent transmission

##### RFS Capabilities

Two-way coherent

Two-way non-coherent (Receive & Lock on S-band)

Uplink transmit S & X down link with frequency controlled by auxilliary or ultra-stable oscillator

S & X band ranging [wide-band and/or one-way ranging on selected mission]

Ranging Channel AGC

One-way transmit S and X or individual frequencies

Earth directable high gain antenna for reception and transmission

Linear S transmit for selected future missions

##### Telemetry required

RFS status

S & X transmitted powers

Temperatures

S/C attitude

Antenna pointing angles

RCVR AGC

Ranging AGC

VCO voltages

Modulation indices



### Table III-2. Deep Space Network Functional Requirements

The capabilities called out in this table match those of the spacecraft and the needs of radio science experimenters. Review of current DSN planning reveals that all of the functions exist or are planned.

Table III-2

#### DEEP SPACE NETWORK

Deep Space Stations, Ground Communications Facility,  
and Network Operations and Control Center

##### Uplink

- S transmit Right hand circular or rotatable linear polarization
- X transmit Right hand circular
- Sufficient power for 20 AU missions - controllable
- Ranging
- Control mod index
- All frequencies tied coherently to station reference

##### Downlink - Closed Loop

- Simultaneously and coherently receive S & X band and count doppler
- Recover range information at S & X
- Produce amplitude information at S & X
- Recover S/C telemetry

##### Downlink - Open Loop

- Simultaneously and coherently receive S & X band right and left hand circular polarization
- Keep signals in receiver passbands either by use of wide band width techniques (digital or analog) or by the use of programmed local oscillators

##### Data outputs

- S & X receiver system
  - Doppler
  - Range
  - Amplitude
  - S/C telemetry

##### Station condition

- Transmitter power and frequency
- Station status
- System calibration
- System temperature
- Antenna pointing angles

#### Significant Event Data

- Open Loop analog and/or digital tapes
- Program local oscillator and/or synthesizer frequencies
- Station logs (hard copy)
- Post track report & calibration data
- Command event files

#### Other Data

- Post track reports
- Solar data
- Weather
- Ionospheric electron content

### Table III-3 Real-Time Radio Science Operations

Experience has demonstrated that real time interaction between the radio science experimenters, the project, and the DSN is necessary during critical operations to maintain data quality and to assure quick recovery from unusual situations. The requirements are based on Mariner 10 and Viking operational experience as reviewed for the Voyager mission. These displays should be available to the experimenter in the mission support area.

Table III-3  
REAL-TIME RADIO SCIENCE OPERATIONS

#### Displays and Hardcopy

##### I. Capabilities Requirements

- A. The program shall have the basic capability to display the following parameters versus the corresponding data time (source of parameter indicated):

1. S-band doppler frequency } (Low rate, data type 37 )
  2. X-band doppler frequency } (High rate, data type 38 )
  3. S-band pseudo residual (TRK-2-14)
  4. X-band pseudo residual (TRK-2-14)
  5. S-band doppler noise (TRK-2-14)
    - a. High rate
    - b. Medium high rate
    - c. Medium low rate
    - d. Low rate
- |  |   |              |
|--|---|--------------|
|  | } | Data type 43 |
|  | } | Radiometric  |
|  | } | validation   |
6. X-band doppler noise (TRK-2-14)
    - a. High rate
    - b. Medium high rate
    - c. Medium low rate
    - d. Low rate
- |  |   |              |
|--|---|--------------|
|  | } | Data type 43 |
|  | } | Radiometric  |
|  | } | validation   |
7. S-X doppler, discrete (TRK-2-14)
  8. S-X doppler, summed
  9. Signal level (TRK-2-14)
  10. Angle 1 (TRK-2-14)

11. Angle 2 (TRK-2-14)
  12. S-band DRVID (TRK-2-14)
  13. X-band DRVID (TRK-2-14)
  14. S-band DRVID noise (TRK-2-14)
  15. X-band DRVID noise (TRK-2-14)
  16. S-band pseudo DRVID (TRK-2-14)
  17. X-band pseudo DRVID (TRK-2-14)
  18. S-X range (TRK-2-14)
  19.  $P_r/N_o$  (TRK-2-14)
- B. The program shall have the capability to continue displaying parameters with time module the full scale time.
- C. The program shall have the capability of translating a full screen Digital Television display to:
1. Half screen vertical
  2. Half screen horizontal
  3. Quarter screen
- consistent with current display capability.
- D. The program shall have capability of displaying up to 12 parameters at the same time, consistent with 3 quad-channel capability.

## II. Operational Requirements

It is a requirement that the operator interface be irreducibly simple; the operator shall specify no more than the following parameters:

1. Station number, spacecraft number
  2. Band (if necessary)
  3. Parameter
  4. Beginning time, full scale time
  5. Lower limit parameter value, full scale parameter value
- to initialize a display.

## III. Test Requirements

Testing shall consist of:

1. Verification of capability and operational requirements.
2. Comparison of Digital Television displays to corresponding tabular NOCC Support Subsystem output for verification of basic graphics accuracy.

### Line Printer

Single and dual-frequency range and doppler observables and ranging system parameters

### TTY

Solar data and DSN post track reports

Voice Nets

Access to mission operations and station through project channels during critical periods.

Computation Capability

1108 Demand terminal and hardcopy unit

Table III-4

NON-REAL-TIME RADIO SCIENCE PROCESSING

The goal of the non-real time processing is to produce a series of tapes which contain all of the calibration, trajectory, radiometric and telemetry data needed by the experimenters. The tapes involved are shown in Figures III-1, 2, 3 and are as follows:

1. Wideband radio science Intermediate Data Record (IDR) which contains all open loop receiver data and housekeeping data in digital form as specified in Document 820-13, Module RSC-11-1, IDR 12-2 (CTA 21 Radio Science System deliverable).
2. Radio Science Intermediate Data Record which contains all open loop receiver and housekeeping data recorded in digital form on computer compatible tape after frequency steering has been accomplished by the programmed local oscillator. Content and format are specified in document 820-13, Module RSC-11-3, IDR 12-1 (DSS Radio Science System deliverable), and Document 824-17.
3. Open loop receiver analog tapes as back-up to the Radio Science IDR. Tapes will be available until such time that the digital IDR system is accepted by the experimenters. The back-up system will then be the Wideband IDR.
4. Tracking IDR which contains closed loop receiver data and Deep Space Station (DSS) information as specified in Document 820-13, Track 2-14 and formatted as Document 900-700 (content summary).
5. Radio Science Calibration delivered by the Tracking System Analytic Calibration (TSAC) computer as defined in Document 820-13, Track 2-12.
6. Trajectory Save Tape (TRAJ SAVE) as defined in Document 618-638 - Software Requirements Document/Software Planning Document Part I Trajectory Analysis Subsystem.
7. User Tracking Data File (UTDF) as defined in Document 900-772 - User Tracking Data File Interface Document.
8. Telemetry EDR (TLM EDR) as defined in Document 820-13, Module IDR 12-1.

## Detailed Performance Requirements (Closed Loop)

PARAMETER	MISSION REQUIREMENTS				ALLOCATION		SYSTEM DESIGN GOAL	FUTURE NEEDS	REMARKS
	VOYAGER JUPITER	SATURN	PIONEER VENUS	GALILEO	S/C	GROUND			
<u>Frequency Band Capability</u>	S up S&X dn	S up S&X dn	S up S&X dn	S&X up S&X dn	NA	NA	-	S,X&K up S,X&K dn	
<u>Received Signal Amplitude Calibration</u>	0.5 db	0.5 db			0.1 db	0.5 db	0.167 db	NSP	Current DSN capability 0.67 db
<u>Received Signal Amplitude Precision</u>									
Error between any two points in a 10 db range	0.033 db	0.033 db				0.033 db	0.0167 db		
Error between any two points in a 40 db range	.167 db	.167 db				0.167 db	0.083 db		
<u>Absolute Frequency of Spacecraft RF Carrier <math>\frac{\Delta f}{f}</math></u>	$5 \times 10^{-12}$	$5 \times 10^{-12}$		$1 \times 10^{-15}$	$2 \times 10^{-12}$	$3 \times 10^{-12}$	$1 \times 10^{-12}$	$1 \times 10^{-17}$	JOP and future need based on gravity wave experiments for averaging times from 30 to 3000 sec
<u>Single Frequency Doppler Phase Stability</u> The error contained in doppler measurements at S or X bands with an integration time of 12 hours	0.367 m	0.367 m				0.33 m	0.1 m	0.1 m	
<u>Dual Frequency Doppler Differential Stability</u> The error contained in differential doppler measurements S-3X/11 with an integration time of 12 hours	0.043 m	0.043 m				0.04 m	0.02 m		Current DSN capability 2m; continued testing and re-design to improve.
<u>Single Frequency Range Calibration</u> The error contained in absolute range measurements made at either S-band or X-band throughout mission lifetime	1.1 m	1.1 m				1.0 m	0.5 m		Current DSN capability 2.5m; continued testing and re-design to improve
<u>Single Frequency Range Delay Stability</u> The variation in the error contained in successive range measurements taken at S-band or X-band over a 12 hour period with signal to noise ratio effects excluded	0.36 m	0.36 m				0.33 m	0.1 m		Current DSN capability 0.5m, continued testing and re-design
<u>Dual Frequency Range Differential Calibration</u> The absolute error contained in differential range measurements, S-X throughout mission lifetime	0.233 m	0.233 m				0.2 m	0.1 m		Current DSN capability 0.33m, continued testing and redesign

## Detailed Performance Requirements (Closed Loop)

PARAMETERS	MISSION REQUIREMENTS		ALLOCATION			SYSTEM DESIGN GOAL	FUTURE NEEDS	REMARKS
	VOYAGER JUPITER	SATURN	PIONEER VENUS	GALILEO	S/C	GROUND		
<u>Dual Frequency Range Differential Delay Stability</u> The variation in the error contained in successive differential range measurements, S-X, in a 12-hour period excluding signal to noise ratio effects	0.033 m	0.033 m				0.03 m	.01 m	Current DSN capability 0.5m, continued testing and re-design

### Detailed Performance Requirements (Open Loop)

<u>Received Signal Amplitude Calibration</u>	0.5 db	0.5 db			0.1 db	0.5 db	.167 db	Requires ex post facto antenna pointing information from S/C. Current DSN capabilities 0.67 m
<u>Received Signal Amplitude Precision</u> for changes in a 30 minute period with $\leq 1$ sec averaging time  Error between two points in a 10 db range Error between two points in a 40 db range	0.033 db	0.033 db			.033 db	.033 db	.0167 db	Requirement comes from need to do differential amplitude measurements to 1" accuracy. Knowledge of DSS open loop receiver noise temperature to 1" accuracy during critical events is necessary
<u>Absolute Frequency Accuracy</u> (1 way) $\frac{\Delta f}{f}$	$1 \times 10^{-11}$	$1 \times 10^{-11}$			$2 \times 10^{-12}$	$1 \times 10^{-11}$	$1 \times 10^{-11}$	Goal is to know frequency of oscillators in open loop system to $< 1 \times 10^{-11}$ with phase noise jitter $< 1 \times 10^{-12}$ . Current DSN performance of the programmed oscillator $< 0.05$ Hz (S-band) yields: $\frac{\Delta f}{f} 2 \times 10^{-12}$
<u>Phase Drift</u> (1000 sec period) S X	$< 36^\circ$ $< 36^\circ \times 11/3$	$< 36^\circ$ $< 36^\circ \times 11/3$						
<u>Differential Phase</u> Between channels SS, XX, S-3x/11	$< 1^\circ$	$< 1^\circ$				$< 1^\circ$		
<u>Absolute Differential Phase</u> Across passband of each channel	$< 1^\circ$	$< 1^\circ$	$< 1^\circ$		NA	$< 1^\circ$		
<u>Receiver Bandwidth</u> S-Band	2.5, 10 kHz	100 kHz	1, 5 kHz		NA	1, 2.5, 5, 10, 100 kHz	NA	
X-Band	7.5, 30 kHz	100 kHz	3, 15 kHz		NA	3, 7.5, 15, 30, 100 kHz	NA	All requirements (other than Saturn ring) stem from prediction system accuracy. Saturn ring experiment bandwidth requirements are preliminary.



# Ancillary Data Requirements

(Time, Earth Atmosphere and Ionosphere, and Navigation parameter requirements which affect and/or correct Radioscience data)

	MISSION REQUIREMENTS				ALLOCATION		SYSTEM DESIGN GOAL	FUTURE NEEDS	REMARKS
	VOYAGER JUPITER	SATURN	PIONEER VENUS	GALILEO	S/C	GROUND			
Calibration data									
Universal Time	4 m sec					4 m sec			
Polar Motion									
X	.7 m					.7 m			
Y	.7 m					.7 m			
Station Time									
Synchronization	20 $\mu$ sec					20 $\mu$ sec			
Distance normal to spin axis	1.5 m					1.5 m			
Longitude	3.0 m					3.0 m			
Relative 2-station Z height	6.0 m					6.0 m			
Earth Troposphere									
Temperature	5°C					5°C			
Pressure	8.3 m Bar					8.3 m Bar			
Relative Humidity	7.3%					7.3%			
Earth Ionosphere									
Faraday rotation 12-hr period	$5 \times 10^{16} \text{ e1/m}^2$					$5 \times 10^{16} \text{ e1/m}^2$			Equivalent to $\sim 1/3 \text{ m } \Delta \text{ range}$
ORVID	.83 m					.83 m			
Multi-Station Doppler, S and X Band and Dual Frequency									
Short Term (60 sec)	.067 m					.067 m			
Long Term (12 hours)	.83 m					.83 m			
3-way Oscillator Offset									
Absolute	1 mm/sec					1 mm/sec			
Stability, 36 hrs	.017 mm/sec					.017 mm/sec			
Simultaneous Dual Frequency Ranging 6 hours	1 m					1 m	.75 m		

#### IV. IMPLEMENTATION

The science rationale as presented in this document represents the state of man's knowledge in 1978. The engineering requirements levied upon the system reflect this knowledge tempered with the realization that the state-of-the-art is still advancing. Similarly, the state of knowledge is still moving rapidly ahead and we can expect both changes and new requirements as results are obtained from future missions. The best and least expensive science will thus come from a developing, dynamic system which is designed to retain flexibility. We have therefore stated hard requirements for known experiments which have identifiable objectives and have specified goals for investigative areas which at present appear to be speculative but, which in fact, are the frontiers of basic science. This document will be updated periodically.

This is an iterative process between science and technology and it is the goal of this document to promote communication between the two while providing an interface document which will get the known jobs done and make the problems visible to all.

Thus, this document should be used through all phases of mission planning. This will assure not only that the system can perform all of the scientific experiments possible but that none will be excluded by oversight or budgetary constraints caused by experiments emerging late in planning. Table IV-1 lists the various phases of a typical project and shows the types of interaction which will maximize the science return for the minimum cost. This is no different from any project interaction with any of the multi-mission or standard equipment efforts though it has been regarded so in the past due to the fact the basic charter is science rather than engineering and cost benefit analysis.

Table IV-1

Radio Science Interaction with Typical Project

Project Phase	MM Radio Science Requirements Document	MM Radioscience Representative	Experiment Reps DSN Systems	NASA Selected Radio Science Team
1. Advanced Planning	↓	↓	↓	
2. Mission Study				
3. Proposal Evaluation		↓		
4. S/C design				↓
5. Ground System Design	↓			
6. Mission Planning				
7. Flight Operations			↓	
8. Science Data Analysis				↓